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Voltage Sag Enhancement of Hybrid PV-wind system using D-STATCOM and SVC

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ABSTRACT

Considered one of the most essential problems of power quality, *Voltage Sag* is related to renewable based distributed generation (DG) units. Using two types of compensators: Distribution Static, also known as (D-STATCOM) and Static VAR, also known as (SVC), this paper handles the issue of voltage sag. Modeling and simulation of hybrid PV-Wind system is proposed in this study. The proposed system is examined under voltage sag incident caused by two factors: a sudden heavy load and faults that are related to short circuit, e.g., single line to ground, double line to ground and three phases to ground faults. A hybrid wind–PV system is presented using MATLAB/ SIMULINK software package. According to the simulation results, the voltage sag is effectively mitigated after using D-STATCOM, which shows efficient voltage recovery compared with SVC.

1. Introduction

Given the fact that renewable energy sources including photovoltaic (PV) systems and wind turbines to the power grid have increased worldwide in terms of their interconnection, power quality has been of utmost importance and gained a lot of interest. Conventional distribution systems contain a primary feeder, secondary feeders, distribution substation, voltage regulators, and distribution transformers. Modern power systems are integrated with renewable energy sources. Fluctuations in renewable energy may affect the process of measuring voltage quality, which is one of the implicit requirements for acceptable operation of the system.

Voltage sags (VS) , voltage swell, interruptions, harmonics and flickering are regarded as the problems predominantly associated with power quality [1]. VS has gained much attention because it occurs frequently in power systems due to many reasons. VS has negative effect on the operation of the end user equipment [2]. VS is defined as voltage decrease from 0.1 to 0.9 per unit in rms voltage for duration between 0.5 cycle to 1 minute [3]. VS are usually related to system faults, energizing of transformers, loading a heavy load and starting of large induction motors. Fig. 1 shows the voltage signal with sag. sensitive equipment is affected by a fault in the transmission line ranging up to hundreds of kilometers away from the fault.

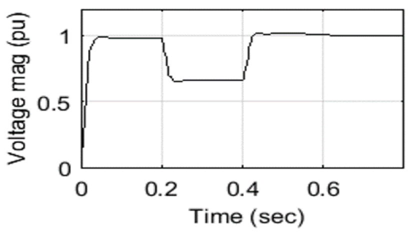

Fig. 1. Voltage Sag

Power quality problems cost unexpected power failures, equipment overheating, damage to sensitive devices, electronic communication interference, increased system losses, decreased efficiency, need for over sizing of installations and many more [4].

Addressing power quality problem is very much primary requirement to deliver clean and standardized power to the consumers. Harmonics and

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load imbalances can be cleared effectively using DSTATCOM or static VAR compensator (SVC). For example, DSTATCOMs are applied for compensating harmonic pollution and load imbalances in the system [5].

Despite the fact that power electronic converters, in compliance with the power quality issues, can be used to merge renewable energy sources with the electric grids, such converters are accompanied with high switching frequency and can add extra harmonic to the system. Depending on voltage source converter (VSC) and a d.c link capacitor, Flexible AC Transmission System (FACTS) controllers have emerged. FACTS controllers can be used to manage the parameters and variables of distribution system, e.g., terminal voltages, and fast and effective voltage angles. They provide both an excellent regulation in the distribution power systems and immediate solution to power quality disturbances. As per requirement, FACTS controllers can function as injecting or absorbing reactive power to a system. One of the main advantages of FACTS controllers is that it helps improve system dynamic behaviour and enhance system reliability [6]. In [7], although the researchers, via a controller known as compensatory fuzzy neural network with an asymmetric membership function (CFNN-AMF) for enhancing the regulation of d.c voltage and power quality, have suggested a D-STATCOM, the dynamic reply of the controller is perceived as moderate.

Recently developed to reduce the problems caused by power quality in the systems of distribution, the distribution FACTs (D-FACTs) or custom power devices, using DSTATCOM, SVC and unified power quality conditioner (UPQC) are the major enabling D-FACTs devices to solve such problems [8]. It also helps implement the filters that are associated with series and shunt active power. This is because UPQC is used to make up for the defects related to voltage and for modifying current harmonics. It selects reactive power injection rating and direction designated as UPQC in order for the voltage to be compensated to a desired value, i.e. 1 p.u, is both analytically and mathematically derived and discussed as using phasor diagram method [9]. The devices mentioned above are used to reduce the losses in a more efficient and effective way. The devices are mounted and fixed near the distribution network, more specifically near the load. Gathered in chain with the supply source, the disturbances associated with the voltage can easily be softened by using the dynamic voltage restorer (DVR). It also decreases the distortion of the voltage waveform [10]. Moreover, when the power supply is regulated and moving without interruption, UPQC is capable of protecting a single load because UPQC features sensitivity. There are many examples of facilities that are known as places with sensitive load. Such places include: hospitals, healthcare centers, transportation facilities and areas for broadcasting news. Except in [11], however, the placement of UPQC and its impact at a certain node among the remaining ones is not investigated yet. This is where the impact of UPQC assignment on undervoltage mitigation of distribution networks is studied. But work is limited to UPQC static shunt compensation, and the effect of UPQC assignment on reducing power loss as well as improvements in line load capacity and voltage stability have not been studied. Constant transfer offset regardless of load demand and UPQC location in the network is not a realistic approach.

In reference [12], the researchers assess and draw a comparison between two things: the classic standard technique and the DC vector control technique, using VSC-based D-STATCOM, to monitor the reactive power and support the network voltage. The proposed D-STATCOM control technique takes advantage of the optimal control design, which relies on a PI controller or PID integration, which is a fuzzy and adaptive-control technique. However, the classical control design performs poorly under the extremely operating conditions. In [13], by comparing the different setting methods, used to calculate the parameters gain of the D-STATCOM controller in the presence of a large probability uncertainty in both the incoming the electrical energy from wind station and the demand of reactive power, thus the performance of the D-STATCOM voltage reactive power control is examined. The reactive power request, which is managed by D-STATCOM, is used to modify the transient voltage in a very short time. In the above paper, only numerical simulations are given to show and prove the control algorithm. The researchers in [14] proposed a new compensation method using D-STATCOM in order to improve the voltage of electrical grid and enhance the transient stability of fixed speed wind turbines in electrical interconnected power systems. In this study, it is shown that the powerful control technology is used in a decentralized system (STATCOM + energy storage system) by enhancing the ultra-low voltage handling ability of constant speed of wind turbines. As with [15], the researchers could calculate and compare two techniques (conventional and modern control) for controlling the reactive power and regulating the network voltage using D-STATCOM. In [16, 17], the performance of D-STATCOM for different values of its controller gain was examined in order to regulate the short-time of transient voltage during high variation of wind turbine load. D-STATCOM select the appropriate magnitude and direction of the reactive power that require to modulate the voltage. In this paper it is proposed to mitigate the voltages sag effects using DSTATCOM and SVC for a hybrid renewable energy system and under varying conditions.

2. Distribution Flexible a.c Transmission System (D-FACTS)

2.1. Static VAR compensator (SVC)

SVC is defined as a shunt-connected VAR generator that is primarily used to improve voltage control and stability. It acts as an injection/absorption of reactive energy from/to the system. It is a parallel combination of thyristor controllable reactors (TCR) and thyristor switched capacitors (TSC). Isolated static compensators (SVC) are used to reduce flickers and are also used to reduce voltage sag, voltage amplification, synchronous asynchronous oscillations and, in the case of fluctuating loads, to smooth out power oscillations [18]. Insulated steam compensators are also used to mitigate power quality in rail feed system, arc furnace, rolling mills, and asynchronous generator system with load fluctuations [19, 20].

2.2. Distribution static compensator

DSTATCOM is an important device in electric power system, when compared with other kinds of devices, it can solve voltage sag, bulge (swell), harmonic distortion, oscillation, flickering, three-phase voltage imbalance and other power quality problems [21], therefore, it has the with great interest in the distribution system and development trend of reactive power compensation and power quality control at present [22-24].

DSTATCOM has powerful function and excellent performance regarding fast load compensation, thanks to small size, low noise, very fast response and many more. With the rapid development of power systems, DSTATCOM will be an important component of modern distribution systems because it will solve the most of power quality issues and will use instead of traditional SVC.

Finally, it was shown that with respect to simulation, the proposed D-STATCOM for very fast load compensation has a wide response rate and unique a small size [25]. DSTATCOM is applied to enhance the electrical reactive power compensation of the constant speed induction motor in thermal power plant [26]. By setting two simple PI controllers at a common coupling (PCC) point, three-phase load voltage compensation was achieved [27, 28].

Being a switch-connected device, DSTATCOM consists, in its simplest form, of three inductors, three VSC legs with six IGBTs and DC power storage as shown in Figure 2. D-STATCOM can be considered as a very active synchronous capacitor, which supply a variable voltage regulating bus interaction as D-STATCOM is connected. Furthermore, D-STATCOM could function as providing a very fast power response or better response than a suppressor [29]. The three-phase generated voltage is connected, using a coupling reactor or coupling transformer, to the electrical power system grid. The active and reactive power flow between the distribution network and DSTATCOM is allowed to be best regulated by correct modulation of the phase and magnitude of the DSTATCOM output voltage [30].

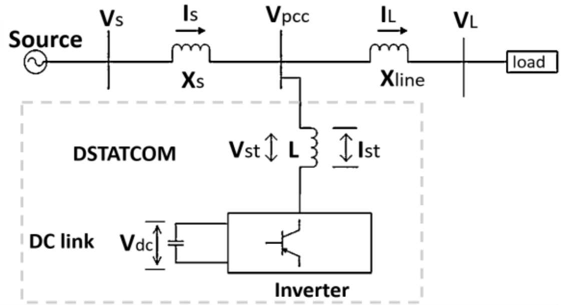

Fig.2. D-STATCOM with the electrical power system.

If $V_L = V_{st}$, no active power or reactive power flow between the grid DSTATCOM. When $V_L < V_{st}$, DSTATCOM will functions as a capacitive reactance and generates capacitive reactive power and the current flows from DSTATCOM to the electric grid. If $V_L > V_{st}$, DSTATCOM acts as an inductive reactance. The reactive power absorbed via D-STATCOM from the grid. The active power and reactive power exchange between test system and DSTATCOM equations are as follows.

$$P = \frac{V_{pcc}V_{st}}{X_t} \sin\delta \tag{1}$$

$$Q = \frac{V_{pcc}^2}{X_t} - \frac{V_{pcc}V_{st}}{X_t} \cos\delta \tag{2}$$

where, V_{pcc} is the voltage magnitude at the point of common coupling (PCC); V_{st} is the voltage of DSTATCOM ; X_t is the total line reactance; δ is the angle delta between bus voltages.

The injected current by the DSTATCOM is evaluated as follows:

$$I_{st} = \frac{V_{st} - V_{pcc}}{jX_t} \tag{3}$$

The DSTATCOM rating can be determined, based on the degree of imbalance and required reactive power compensation. The DC bus voltage level is included in the VSC model, which appears on the DC bus capacitance and affects the switch rating. The minimum voltage magnitude of DC bus in the VSC of DSTATCOM must be greater than twice the maximum (peak) phase voltage of the distribution system [31]. The DC bus voltage is rated as:

$$V_{dc} = \frac{2\sqrt{2}V_{pcc}}{\sqrt{3}m} \quad (4)$$

Where, The DC bus capacitor design is based on the instantaneous power available to D-STATCOM during the transient state. m is the generally assumed modulation index of 1 or 0.8. The principle of energy conversion is applied as follows:

$$\frac{1}{2}C_{dc}(V_{dc}^2 - V_{dc1}^2) = 3V\alpha It \quad (5)$$

where, C_{dc} is capacitor value; I is a phase current in Amper; α is the over-loading factor; V is a phase voltage in Volt; V_{dc1} is the minimum d.c voltage level; $V_{dc}$is the nominal d.c voltage; t is the time required for d.c bus voltage recovery.

Selecting the inductance (L_f) of VSC is depended on current ripple(I_{cr}), switching frequency (f_s) and d.c bus voltage (V_{dc}) and evaluated as :

$$L_f = \frac{\sqrt{3}mV_{dc}}{12\alpha f_s I_{cr}} \quad (6)$$

At half the switching frequency, the setting of high-pass filter is done and used for reduce the noise or the switching ripples from the point of common-coupling.

3. System Under Study

The model has a 0.6 MW solar connected electric power system grid, a Dual Feed Induction Generator (DFIG) based on a 1.2 MW wind turbine and an R-L load. The system is tested with and without D-FACTS (SVC and DSTATCOM) during overloads and short-circuit faults (one line - ground, double line - ground and three lines - ground as shown in Figure 3.

Mechanical energy is converted by DFIG from an aerodynamic system into alternating current electrical energy, which is transmitted, via two paths, and then to the belt. Whereas the main path is the directly connected stator link, the secondary path is the rotating circuit that supplies power through two series transformers. The amount and direction of energy flowing through the rotating circuit depends on the point of operation of the induction machine. The electrodynamic model of induction machines was developed [33]. DFIG-based variable speed wind turbines transmit power to the grid through two main paths. It is noteworthy that most of the power is transmitted through the stator and only a small part is fed through the rotating circuit and the transformer. The first transformer is known as the rotor side transformer, and it is connected to the DFIG's rotor coils. Known as the network bypass switch, the other is connected to the network in the PCC via an AC filter. The DC terminals of the two transformers are combined with a DC shunt capacitor. The power scheme of each transformer simply consists of a three-legged VSI. However, from a control perspective, different control systems based on control functions can be applied to inverter switches.

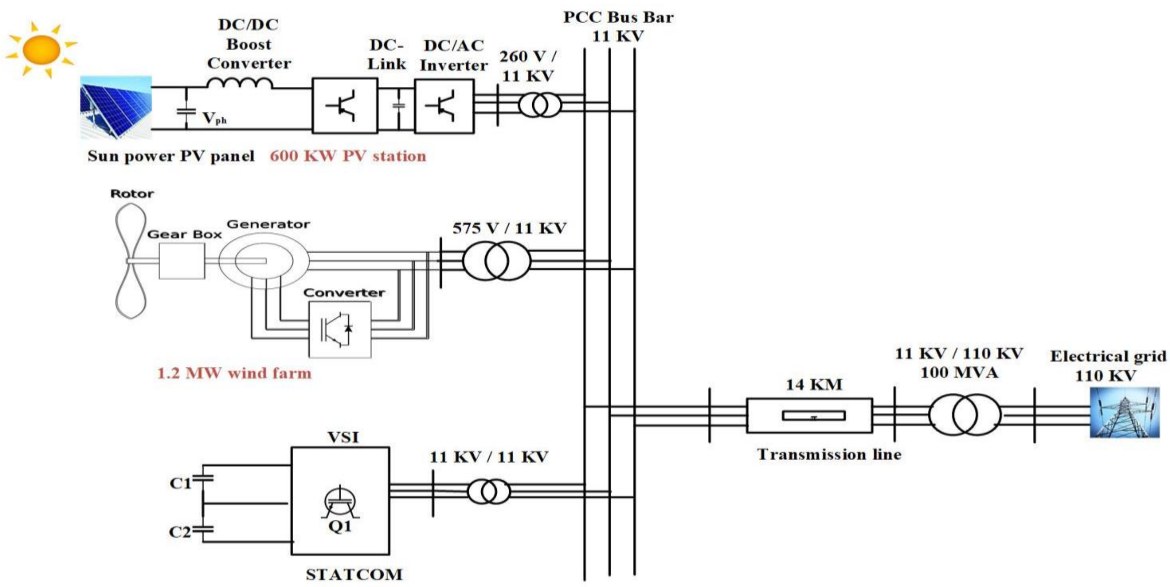

Fig.3. proposed Grid with PV/wind hybrid power system and D-STATCOM.

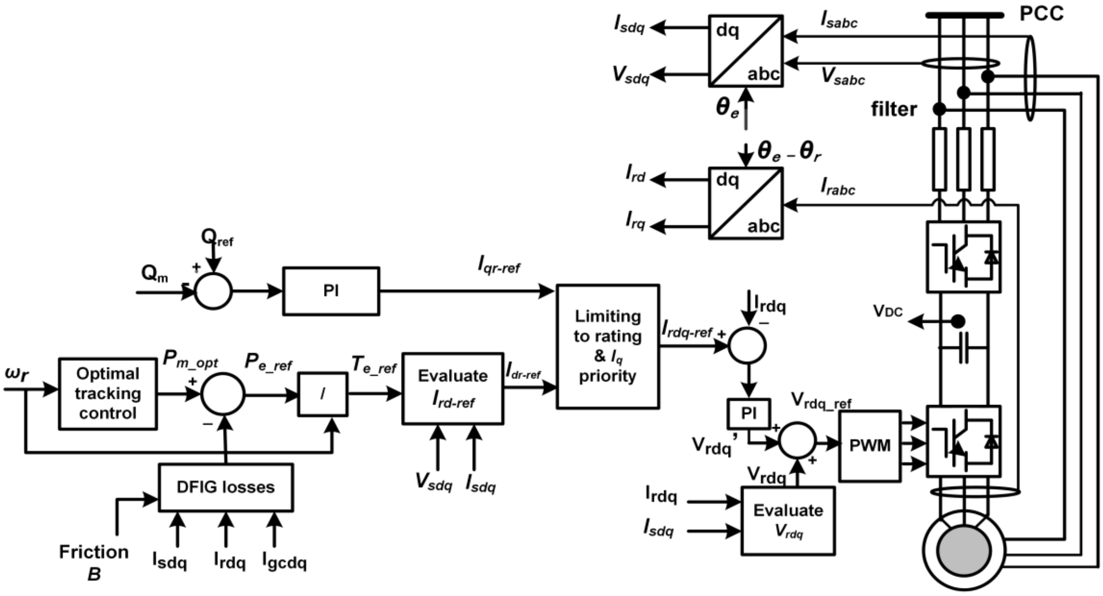

Fig.4. Control scheme of rotor side converter.

Rotor side converter control is mainly used to control the active power to extract the maximum power from the wind. Furthermore, to control the reactive power in order to maintain the magnetization level and achieve the reactive power setting (ie operating at the PF unity). Maximum power capture is achieved by controlling the required mechanical power with the rotation of the generator speed in its optimum relationship according to the power signal feedback idea based on the current mode control. Often the generator speed control is achieved through the rotary bypass converter as shown in Figure 4 which allows the generator to adjust the rotational speed depending on the optimum wind energy tracking [34, 35].

The PV station contains a lot of many electrically PV modules and it is connected in series to reach the high level of voltage. Also, in order to obtain the required power capacity, a large number of PV series are connected in parallel to form a PV array. In addition, in order to obtain maximum power under different solar radiation, each PV array is connected to a DC/DC boost converter. Then, in parallel, the photovoltaic arrays are linked with the main VSI. Maintaining constant DC junction voltage, injecting active power into the electrical grid, and achieving the required reactive power are the main objectives of VSI. This configuration is characterized by low losses, cost-effectiveness, constant DC voltage, and higher efficiency [36]. The electrical PV array Modeling based on the Shockley diode is shown in Fig. 5. The identical current-voltage relationship of the PV can be calculated by [37].

$$I = N_p I_{ph} - N_p I_s \left\{ \exp\left[\frac{q\left(\frac{V}{N_s} + \frac{R_S I}{N_p}\right)}{KTA} \right] - 1 \right\} - \left(\frac{\frac{N_p V}{N_s} + R_s I}{R_{sh}} \right) \quad (7)$$

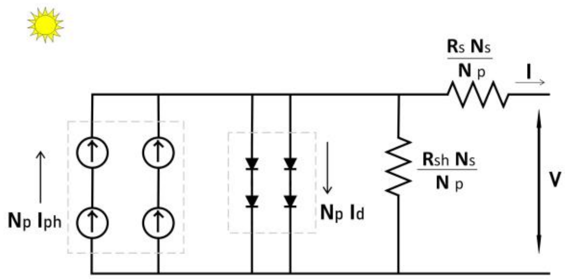

Fig.5. The equivalent circuit of PV array.

4. Simulation Results

The studied system is first examined against different faults and its voltage level is recorded Table 1. In this case voltage level is not accepted technically, therefore, the system is reinforced by DSTATCOM and SVC. After using SVC, the voltage has improved to the accepted value even with over loading condition as shown in Fig 6. But SVC failed to improve the voltage to reach the accepted value during short circuit faults as shown in Fig. 7. After using D-STACOM during short circuit faults and over loading both separately the voltage has improved to the accepted value at each condition. The voltage sag has reduced after using DSTATCOM, furthermore, DSTATCOM shows efficient voltage recovery compared with SVC as shown in Figs. 6-9. and Table 1.

4.1. The system without D-FACTS

In this study case, different faults are placed at the PCC for 0.2 sec. In single line to ground fault case, the voltage magnitude decreased from 1 pu to be 0.83 pu at the PCC voltage and indicated in Fig. 6. Also, the voltage magnitude decreased to 0.7 pu in case of double line to ground fault as shown in Fig. 7. In three line to ground fault case, when the fault resistance R_{on} = 0.5 Ω the voltage decreased to 0.55 pu at the PCC voltage as indicated in Fig. 8. After adding a heavy load to the system, the voltage magnitude decreased to 0.8 pu as shown in Fig. 9.

4.2. The effect of SVC

In this study case, double line to ground fault and a sudden heavy load are placed at the PCC. In double line to ground fault case, the SVC has improved the voltage magnitude from 0.7 to 0.75 (p.u) at the PCC as indicated in Fig. 7. After connecting a heavy load to the system with SVC at PCC the voltage magnitude has improved from 0.8 to 0.98 pu as shown in Fig. 9.

4.3. The DSTATCOM effect

The PCC voltages after compensation using the modified DSATCOM become balanced and accepted value at different short circuit faults and overloading condition. In single line to ground fault case with using DSTATCOM the voltage sag has improved to accepted value as shown in Fig. 6. Also, the voltage magnitude of the double and three line to ground faults at PCC has improved to 0.99 pu and 0.96 pu after using DSTATCOM as shown in Figs. 7, 8. In the case of adding a sudden heavy load, the DSTATCOM could raise the voltage magnitude from 0.8 pu to 1 pu as shown in Fig.9 and Table 1.

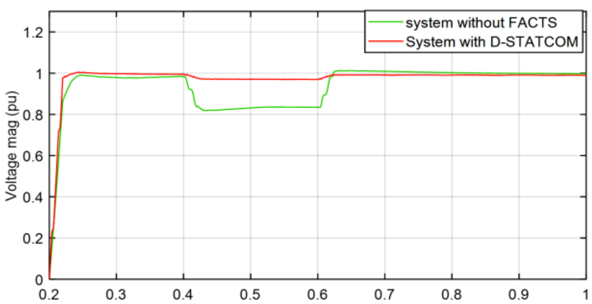

Fig. 6. Single-line to ground voltage magnitude with and without D-STATCOM.

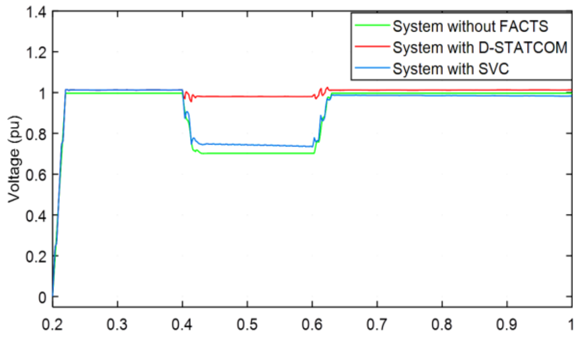

Fig. 7. Double line - ground voltage magnitude with and without D-FACTS.

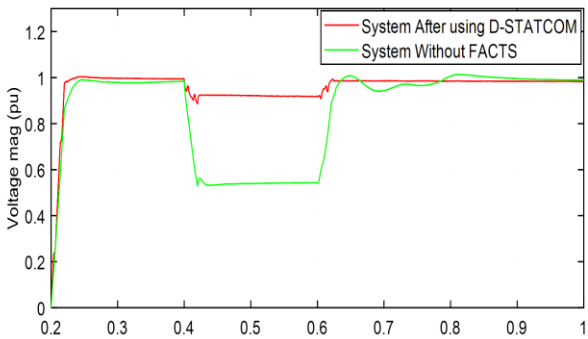

Fig.8. Three phase - ground voltage magnitude with and without D-STATCOM.

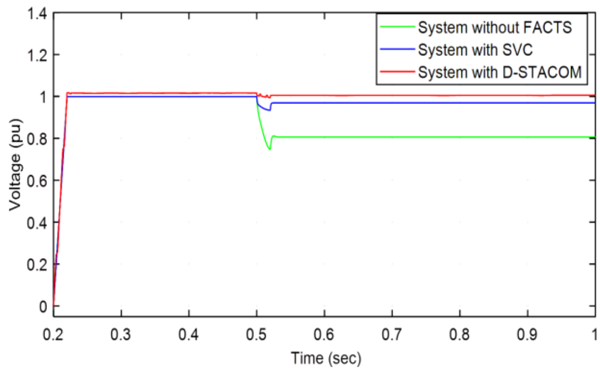

Fig. 9. The voltage magnitude during a sudden heavy load with and without D-FACTS.

Table 1. The voltage magnitude during short circuit faults and over loading with and without D-FACTS

D-FACTS	The Voltage magnitude (pu)			
	Single line - ground fault	Double line - ground fault	Three phase - ground fault	Over loading
Without	0.83	0.7	0.55	0.8
SVC	0.88	0.75	0.6	0.98
DSTATCOM	0.99	0.99	0.96	1

5. Conclusions

In this paper, modeling and simulation of SVC and DSTATCOM equipped in hybrid PV-wind system is presented by using MATLAB/ SIMULINK software package. The proposed DSTATCOM is used for reducing voltage sag caused by a sudden heavy load and short circuit faults such as single line - ground, double line - ground and three phases to ground faults. According to the simulation results, the voltage sag is mitigated after using DSTATCOM further, DSTATCOM shows efficient voltage recovery compared with SVC.

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